Unveiling the relationships between biochar characteristics and its beneficial effects in the anaerobic digestion of the organic fraction of municipal solid waste (OFMSW)

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Introduction

Municipal solid waste (MSW) landfilling is one of the main contributors to environmental pollution. Public entities have since been inciting the source-separation and valorisation of the organic fraction of MSW (OFMSW) in the framework of circular economy (Directive 2018/851/EU). Anaerobic digestion (AD) is an established waste-to-energy technology that enables the recovery of biogas and a nutrient-rich digestate that can be use as fertiliser, but still faces some challenges. These are mainly the low methane (CH_4) content in biogas (50-70%) compared to natural gas (>95%), and the process sensitivity to microbial activity inhibition. Biochar supplementation is gaining interest as a strategy for AD improvement, as this carbon-based material shares many desirable properties with activated carbon but can be produced from biowaste. Extensive meta-analyses by Chiappero *et al.* (2022) and Xiao *et al.* (2021) proved that biochar can improve AD performance under certain conditions, but its beneficial effects depend on many factors and the complex correlations between them are yet to be understood. This study seeks to elucidate the relations between biochar properties and its effect on AD performance by testing biochars obtained from three feedstocks at three pyrolysis temperatures on CH_4 production and CH_4 content.

Materials and methods

The AD substrate and inocula were collected from a full-scale plant located in Barcelona (Spain) treating source-selected OFMSW under wet (below 10% TS) and mesophilic (40-42 ºC) conditions. Wood-derived biochars were facilitated by the Centre for Forestry Science and Technology of Catalonia (CTFC) and characterised in terms of calorific value and elemental composition. They were produced from three feedstocks (*Pinus pinea*, *Pinus halepensis* and *Quercus suber*) at three pyrolysis temperatures (300, 400 and 500 ºC), resulting in a total of nine biochars (PP300, PP400, PP500, PH300, PH400, PH500, Q300, Q400 and Q500). BMP tests were performed in 250 mL (150 mL working volume) glass bottles according to Angelidaki *et al.* (2009). Biochars were added in a 5% dose based on TS (dry weight) following previous findings (García-Prats *et al.*, 2024) and compared to the control (no biochar addition). Methane production was determined according to Casals *et al.* (2014). Biogas production was measured as headspace pressure with a manometer and transformed into volume using the ideal gas law. Biogas composition in CH_4 and carbon dioxide (CO_2) was measured with a GC 7820A gas chromatographer (Agilent, USA) and used to calculate the CH_4 production (NmL g^{-1} VS). The effect of biochar on CH_4 content and production was assessed through analysis of variance (ANOVA) tests using SigmaPlot 12.0 software (Systat, USA). Regression analyses and Principal Component Analysis (PCA) were performed using OriginPro 2021 software (OriginLab, USA) to study the role of biochar characteristics on AD performance.

Results and discussion

The CH_4 production (Table 1) increased with the addition of all the biochars tested (430-477 NmL g^{-1} VS) at a 5% dose compared to the control (421 ± 33 NmL g^{-1} VS). This increase only proved significant with biochars Q400 (p-value=0.020) and Q500 (p-value=0.023), yielding 13.2 and 11.8% more CH_4, respectively. A two-way ANOVA test among biochars revealed that overall, the pyrolysis temperature had bigger effect on CH_4 production (p-value=0.477) than the feedstock (p-value=0.539). Regarding biogas composition (Table 2), the CH_4 content of biogas was considerably high (66-67%) in all conditions. Biochar-supplementation at 5% resulted in slightly lower CH_4 concentrations (66.6 ± 0.5%) than the control (67.6 ± 0.5%). This decrease was significant in biochars PH300 (p-value=0.032), Q300 (p-value<0.001) and Q400 (p-value=0.013), but the differences were very small in all three cases (1.8, 2.4 and 1.9%, respectively). The regression analyses found no strong correlations (R^2>95%) between biochar characteristics (calorific value and C, H, N content) and AD performance (CH_4 production and CH_4 content) at a 5% dose. PCA analysis (Figure 1) yielded two primary components accounting for 89.88% of total variance. Although these are only preliminary results, it can be seen that the conditions found in the positive side of both components (PH500, Q400 and Q500) are those with the best CH_4 production values (over 10% increase compared to control), confirming previous findings.

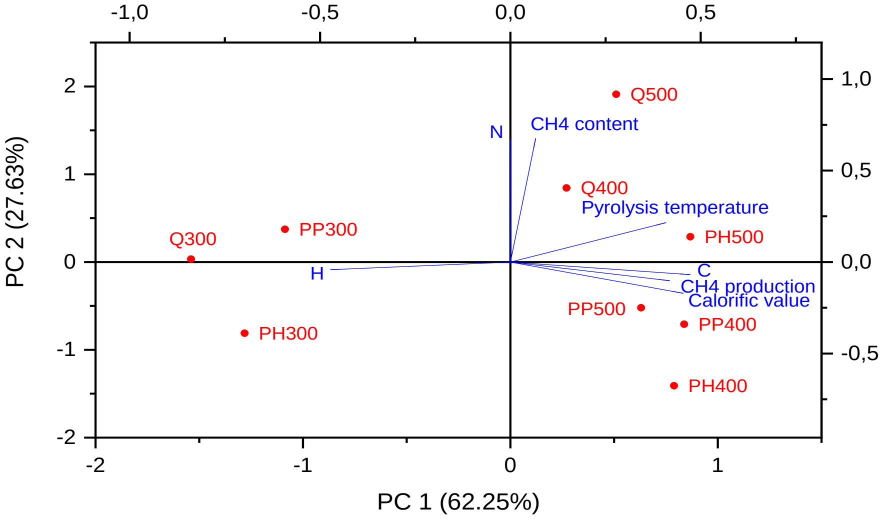
Table 1. Accumulated CH_4 production (NmL g^{-1} VS) at 21 days of the biochar-supplemented reactors (5% based on TS), and increment (%) compared to the control (421 ± 33 NmL g^{-1} VS). The results are presented as the average and standard deviation of quadruplicates. Significance is represented with an asterisk (*).

Feedstock / Pyrolysis temperature (ºC)	300	400	500
PP (*Pinus pinea*)	452 ± 15 (+7.2%)	462 ± 53 (+9.5%)	448 ± 27 (+6.2%)
PH (*Pinus halepensis*)	440 ± 20 (+4.5%)	430 ± 66 (+2.0%)	470 ± 25 (+11.4%)
Q (*Quercus suber*)	442 ± 51 (+4.8%)	477 ± 12 (+13.2%)*	471 ± 16 (+11.8%)*

Table 2. Average CH_4 content (%) at steady-state (day 3 to 21) of the biochar-supplemented reactors (5% based on TS) and increment (%) compared to the control (67.5 ± 0.5%). The results are presented as the average and standard deviation of quadruplicates. Significance is represented with an asterisk (*).

Feedstock / Pyrolysis temperature (ºC)	300	400	500
PP (*Pinus pinea*)	66.7 ± 0.4 (-1.3%)	67.0 ± 0.3 (-0.9%)	66.5 ± 0.3 (-1.6%)
PH (*Pinus halepensis*)	66.4 ± 0.3 (-1.8%)*	66.7 ± 0.6 (-1.3%)	66.8 ± 0.2 (-1.1%)
Q (*Quercus suber*)	66.0 ± 0.7 (-2.4%)*	66.3 ± 0.4 (-1.9%)*	67.2 ± 0.4 (-0.6%)

Figure 1. Principal Component Analysis (PCA) of biochar properties and AD performance for all the biochars tested (PP300, PP400, PP500, PH300, PH400, PH500, Q300, Q400 and Q500) at a 5% dose (based on TS).



Conclusions

Biochar supplementation at 5% (based on TS) can improve the AD of the OFMSW by increasing CH_4 production up to 13.2%, but this is subject to the material characteristics. Establishing clear correlations between biochar properties and AD performance proved difficult. The BMP test is currently being replicated with a higher biochar dose (10% based on TS) in the expectation of obtaining more evident effects that will facilitate drawing conclusions from ANOVA, regression and PCA analyses. Further biochar characterisation analyses (TGA, metal content, feedstock composition, etc.) are also being conducted to complement the aforementioned analyses.

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